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CDF modelling for the optimum tilt and azimuth angle for PV installations: case study based on 26 different locations in region of the Yorkshire UK

Mahmoud Dhimish [1*], Peter Mather [1], Violeta Holmes [1], Martin Sibley [1]

[1] Department of Engineering and Technology, Laboratory of Photovoltaics, University of Huddersfield, Queens gate HD1 3DH, Huddersfield, United Kingdom
[*]M.A.Dhimish@hud.ac.uk

Abstract: The optimum tilt and azimuth angle for PV installations in twenty-six different locations within the county of Yorkshire, UK have been evaluated. In order to examine the performance of the PV systems, a selection of criteria has been identified as follows: (i) the maximum difference in the age of the PV installations is no older than 2 years, (ii) PV modules technology is crystalline-Silicon (c-Si), (iii) maximum area of study in each location is 20 km^2, and (iv) PV systems have either the same tilt or azimuth angle within ±2°. The Huddersfield area was used as the primary example to evaluate the proposed methodology. The optimum tilt and azimuth angle for PV installations in the area is 39°, and -1° respectively. Moreover, based on 4 kWp PV installations observed in all studied locations, a geographical map representing the annual energy production in the twenty-six locations has been drawn. The maximum annual energy production is observed for the city of Hull, whereas the minimum observed for the town of Keighley. Finally, the evaluation of the overall annual energy production is discussed using the analysis of the direct normal irradiance (DNI), ambient temperature, air frost, and the cloudiness.

1. Introduction

The output energy yield of Photovoltaic (PV) systems strongly depends on weather conditions such as wind speed [1], humidity [2], temperature, solar irradiance, and some other factors such as dust/dirt [3], hot spots [4-5], snow [6], and micro cracks [7-8]. Moreover, the tilt and azimuth angle of PV installations play a major role in increasing the annual energy yield production.

Empirical formulas were employed in early studies to estimate the optimum tilt angles at different sites, which are only related to local altitude described in [9]. Later, the authors in [10] explained that PV modules should be installed with the tilt angle of 2.8º greater than the latitude.

In 2017, the authors [11] proposed an analysis of the optimum tilt angle for soiled PV panels, where it was found that the optimum tilt angle for PV modules is between 25.89º to 26.06º in dusty weather conditions. Authors in [12-13] estimated the optimum tilt angle for PV panels in the Saudi Arabia. It was found that PV panels tilt angle must be changed during the season of the year to increase the total energy production of a PV system by at least 6.38 %.

In other related studies, several recommendations for a fixed tilt and azimuth angle have been suggested based on various locations in the following countries: South Africa [14], Syria [15], India [16], Iran [17], United States [18], Turkey [19], and United Arab Emirates [20]. Moreover, various studies on the optimization of tilt angles have considered the effect of cloudiness [21], wind speed cooling [1], maximizing radiation on flat plate collectors [22], clearness index optimization method [23], radiation transfer method [24], and maximizing different solar radiation in different geographical locations [25-26]. These methods are used to draw a relevant map for PV installations tilt and azimuth angles, thus, enhance the generation of the annual energy of PV systems.

Most recently, in 2018, the authors in [27] proposed two predictive models to develop a single-axis tracking systems which could determine the optimum position of PV panels. The study has been validated on some European Baseline Surface Radiation Network (BSRN) stations for the year 2015.

It is of interest that there is still a lack of empirical observations based on various PV systems installed in different locations within the same studied area. Another limitation found in the literature is that for instance there are few articles studied the impact of tilt and azimuth angle of PV installations based on an annual energy production for several years. Therefore, this article attempts to fill-in this gaps in knowledge found in the literature.

The tilt is the angle of the PV modules from the horizontal plane, for a fixed (non-tracking) mounting [28], whereas the azimuth is the angle of the PV modules relative to the direction due south (-90º is east, 0º is south, and +90º is west) [29-30].

M. Z. Jacobson & V. Jadhav [31] found that the optimal tilt angle should vary at the same latitude, depending on cloud cover, due to the variation of direct versus diffuse radiation with cloud cover.

Firstly, a database of more than 3600 installed PV installations in the region of Yorkshire shown in Fig. 1 were observed. The access for the database was taken from Solar UK, which is one of the top leading companies in UK and Europe for PV installations. From the observed database, it was found that most PV installations capacity is 4 kWp, because that is the PV capacity which the UK government supported over the previous 10 years. However, some other PV systems with a capacity varying between 1.9 - 3.5 kWp.

In this article, the calculation of the optimum tilt and azimuth angle for twenty-six different locations, based on real time long term data measurements have been studied. The annual energy production in each location has been observed and a geographical map presenting the estimated annual energy generation was drawn. Lastly, the tilt and azimuth angles for all studied locations are known.

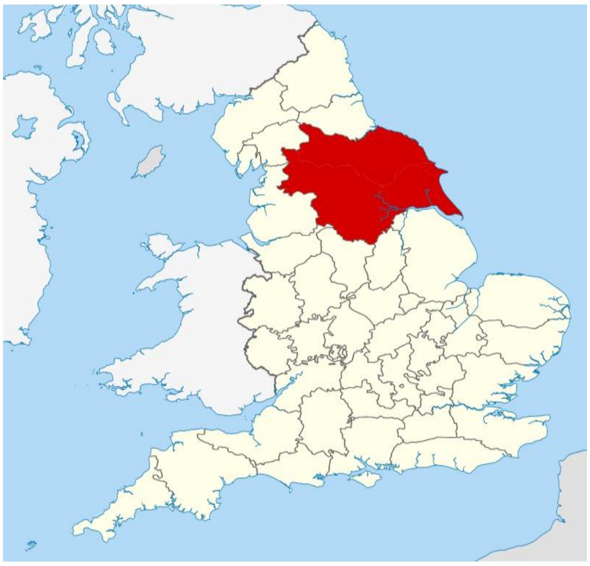


Fig. 1. *Yorkshire County, United Kingdom*

Table 1 Examined PV locations across Yorkshire

Location Number		Coordinates Latitude / Longitude
	City	
1	Sheffield	53°22′58″ N / 1°27′57″ W
2	Leeds	53°47′47″ N / 1°32′52″ W
3	Bradford	53°47′38″ N / 1°45′07″ W
4	Hull	53°44′40″ N / 0°20′06″ W
5	York	53°57′27″ N / 1°04′57″ W
6	Wakefield	53°40′59″ N / 1°29′51″ W
7	Ripon	54°08′08″ N / 1°31′41″ W
	Town	
8	Huddersfield	53°38′56″ N / 1°47′02″ W
9	Doncaster	53°31′22″ N / 1°07′52″ W
10	Rotherham	53°25′48″ N / 1°21′24″ W
11	Barnsley	53°32′59″ N / 1°28′59″ W
12	Halifax	53°43′00″ N / 1°51′00″ W
13	Harrogate	53°59′26″ N / 1°32′14″ W
14	Keighley	53°52′04″ N / 1°54′23″ W
15	Dewsbury	53°41′26″ N / 1°37′44″ W
16	Scarborough	54°16′46″ N / 0°24′15″ W
17	Batley	53°42′10″ N / 1°38′01″ W
18	Redcar	54°36′59″ N / 1°03′35″ W
19	Thornaby	54°31′59″ N / 1°18′00″ W
20	Northallerton	54°20′20″ N / 1°25′56″ W
21	Sebly	53°47′01″ N / 1°04′03″ W
22	Driffield	54°00′22″ N / 0°26′41″ W
23	Pocklington	53°56′00″ N / 0°46′51″ W
24	Thrisk	54°56′00″ N / 1°20′29″ W
	Village	
25	Cottingham	53°46′50″ N / 0°24′55″ W
26	Brotton	54°34′00″ N / 0°56′22″ W

2. Methodology

In order to evaluate the optimum tilt and azimuth angle in the studied locations (Yorkshire), twenty-six city/town/village are studied. The coordinates and locations are listed in Table 1.

To test and compare between the optimum tilt and azimuth angle in each studied location, the investigation of residential PV systems at the same city/town/village, with various tilt, azimuth, and PV capacity size were taken into account. However, to compare between the PV installations within a specific location, we have set the following selection criteria:

- The maximum difference in the age of the PV modules was no great than 2 years.
- PV module technology is crystalline-Silicon (c-Si).
- Maximum area per location set to 20 km^2.
- PV systems have either the same tilt or azimuth angle within ±2 degrees.

According to the third selection criteria (maximum area of study 20 km^2), Fig. 2 shows an example of one of the studied areas at Huddersfield town. The total area is 19.99 km^2.

Next, the PV installation data will be normalized based on the PV system size of installation using (1). The normalization process is important since the examined PV installations capacity varies between 1.9 kWh and 4 kWh. Therefore, all will be normalized between 0 and 1.

$$\text{PV Energy}_{\text{normalized}} = \frac{\text{Measured PV Energy}}{\text{Maximum Estimated PV Energy}} \quad (1)$$

The maximum estimated PV energy is simulated using LabVIEW software, whereas the minimum and maximum normalized data are within 0 and +1 respectively. Most of the PV systems observed in this article have a capacity of 4 kWp, because that is the PV capacity which UK government supported over the last 10 years.

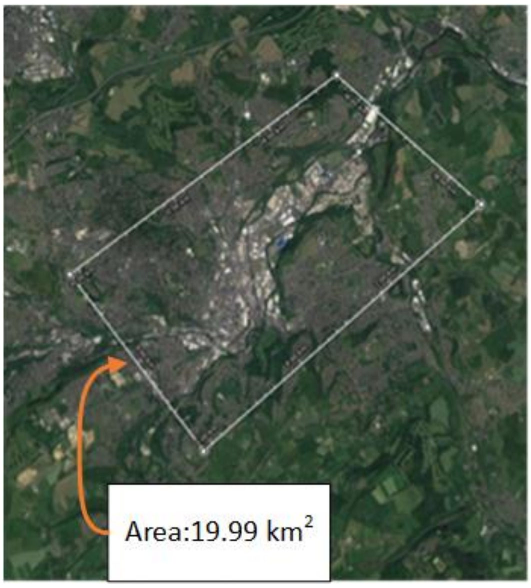


Fig. 2. *Geographical map presenting Huddersfield study area, where the total investigated area is 19.99 km^2*

3. Methodology Evaluation

The Huddersfield study area is shown in Fig. 2. This area contains 127 PV installations which fits with the criteria set in the methodology section (section 2). Two different evaluation processes are tested (tilt angle and azimuth angle), the results and the specifications for each evaluation process is as follows:

3.1. Tilt Angle Evaluation

In order to evaluate the tilt angle of the selected area, a number of conditions are applied to all PV installations, these conditions are as follows:

- **All PV systems are integrated on the roof of a building:** since the PV integration might change the energy production. For example, PV modules installed in farms might be affected by dust/dirt more frequently than the PV modules integrated on the roof of buildings.
- **PV age of installation 2009 – 2010:** in the studied area, there are a number of new PV installations (2016 and 2017). Therefore, the PV modules have been affected by weather conditions such as fluctuations of wind, humidity, temperature and solar radiation less than older PV systems. From the observed PV database, it was found that most of the examined PV systems were installed between the years 2009 and 2010, thus their energy production was compared accordingly.
- **Azimuth angle fixed at -5º to -4º:** since this section describes the behavior of the PV systems in various tilt angles, the compared PV systems have the same azimuth angle.

The monthly normalized energy of the examined PV installations with different tilt angles various between 31º and 46º are reported in Fig. 3(a). Where it is evident that the energy production varies across all examined tilt angles. An example for a PV system installed at tilt angle 46º is shown in Fig. 3(b), in January, February, November, and December the PV systems produces the maximum output energy. However, the PV systems installed at this angle produces the minimum output energy during the summer (May, June, July, and August).

From all tested PV installations, it was found that PV systems installed at tilt angle of 39º have almost the intermediate range of the generated energy production comparing to all other tilt angle during the year. This result is labelled in Fig. 3(c) by the dashed line.

As a conclusion, the average annual energy production of all the examined PV systems installed at different tilt angles are illustrated in Fig. 3(d). It is shown that PV installations with tilt angle of 31º generates an annual energy of 3427 kWh, whereas PV installations at tilt angle of 39º achieves the maximum energy production of 3519 kWh. Therefore, this tilt angle (39º) is found to be the optimum across all other examined PV tilt angles for the Huddersfield study area. It is worth remembering that the compared PV installations have the same capacity of 4 kWp.

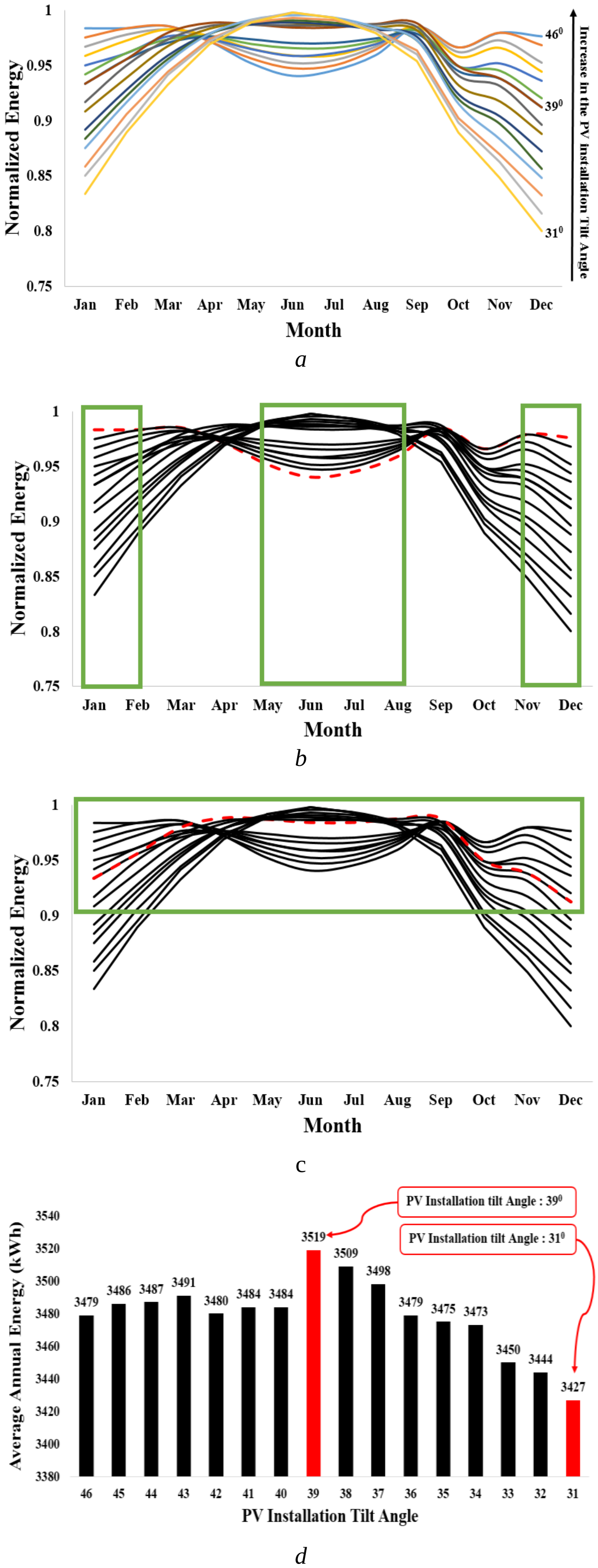


Fig. 3. *Tilt angle evaluation results*

***(a)** Monthly normalized energy for various PV systems installed at different tilt angle, **(b)** Example for a PV system installed at tilt angle 46º, **(c)** Optimum PV tilt angle at 39º, **(d)** Comparison for the average annual energy production for different PV systems installed at different tilt angles*

3.2. Azimuth Angle Evaluation

This section describes the evaluation of PV installations with various azimuth angle at the studied area (Huddersfield). There are a number of conditions that must be applied to make comparisons between the PV installations. The conditions are as follows:

- **All PV systems are integrated on the roof of a building**
- **PV age of installation 2010 – 2011:** from the observed PV database, it was found that most of the examined PV systems that have fixed tilt angle with various azimuth were installed between the years 2010 and 2011
- **Tilt angle fixed at 41º:** since this section describes the behavior of PV installations at different azimuth angle, the PV tilt must be fixed. It was found from the database of the observed PV installations containing various PV systems installed at tilt angle 41º, with a number of azimuth angle varies between -17º, and 30º

PV installations with different azimuth angles between -17º and 30º have been studied. Ten different azimuth angles were taken into account: -17, -11, -7, -3, -1, 3, 11, 20, 23, and 30 degrees. In addition, the PV installations capacity is 4 kWp.

The monthly normalized energy is shown in Fig. 4(a). As can be described, PV systems installed at azimuth angle of 30º have the lowest normalized energy production throughout the year. However, PV systems installed at azimuth of -1º have the highest monthly-normalized energy; this result is labelled on Fig. 4(b) by the dashed line.

The average annual energy production of all examined PV systems installed at different azimuth angle are presented in Fig. 4(c). This figure shows that the lowest annual energy production is obtained for the PV systems installed at 30º. However, the ideal installation azimuth angle is at -1º with an annual energy generation of 3517 kWh. The second and third best choices for the azimuth angle are observed for PV systems installed at -3º, and -7º respectively.

Despite the fact that the annual energy production of PV systems strongly depends on weather conditions such as wind speed, humidity, temperature, and solar irradiance; on the other hand, the tilt and azimuth angle play major role in order to maximize the energy production of PV installations. This section shows that the loss in the energy production due to the change in the azimuth angle of the PV installations potentially reach up to 118 kWh, this result is calculated as follows:

3517 (azimuth -1º) – 3399 (azimuth 30º) = 118 kWh

Furthermore, in the previous section it was evident that the annual energy production of PV installations strongly depends on the tilt angle, where the maximum energy loss could reach up to 92 kWh based on data observed from 4 kWp PV installations, this is calculated as follows:

3519 (tilt 39º) – 3427 (tilt 31º) = 92 kWh

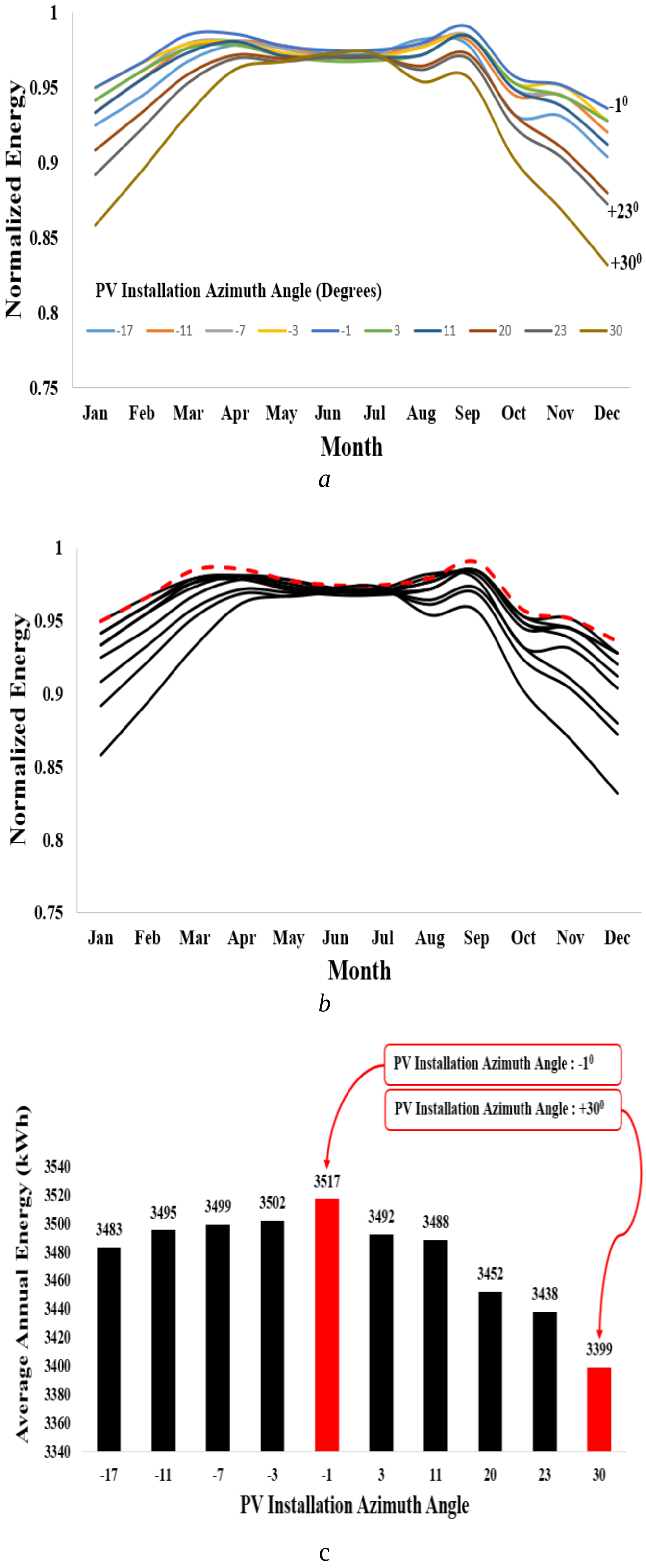


Fig. 4. *Azimuth angle evaluation results*

(a) *Monthly normalized energy for various PV systems installed at different azimuth angle,* ***(b)*** *Optimum PV azimuth angle at -1º,* ***(c)*** *Comparison for the average annual energy production for different PV systems installed at different azimuth angle, where the maximum energy production is obtainable at azimuth angle of -1º*

4. Results of Methodological Evaluation

This section presents the optimum tilt and azimuth angle for all twenty-six observed locations. In addition, the studied location will be compared based on the yearly PV energy production based on 4 kWp PV installations.

Based on the methodology described earlier in section 3, the optimum tilt and azimuth angle for all studied locations are analysed and reported in Table 2. It is evident that each location has almost different tilt and azimuth angle. Huddersfield area has an optimum tilt and azimuth of 39°, -1° respectively, this result briefly described in section 3.

As shown in Table 2, Hull region has the highest annual energy production of 4010 kWh, whereas the lowest energy production is observed for Keighley at 3350 kWh. Fig. 5 summarizes the annual energy production from all studied locations (max to min). Additionally, the yearly in-plane irradiance (kWh/m^2) is shown in Table 2. Locations with low yearly in-plane irradiance such as Keighley, Northallerton, and Bradford city generates less energy compared to locations that have higher irradiance profile such as Hull, Cottingham, and Scarborough.

Based on the data analysed from 4 kWp PV installations shown in Fig. 5, the PV locations have been categorized as follows:

- **Category 1:** locations have an annual PV energy more or equal to 3600 kWh
- **Category 2:** locations have an annual PV energy more or equal to 3500 kWh but less than 3600 kWh
- **Category 3:** locations have an annual PV energy less than 3500 kWh

Remarkably, these three categories were used to plot a geographical map for the distribution of the estimated annual energy production for all studied locations. It is worth remembering that all the data is based on 4 kWp PV installations with optimum tilt and azimuth angle (reported in Table 2).

Table 2 Optimum azimuth angle, tilt angle, yearly energy production and in-plane irradiance in the examined locations

Location	Optimum tilt angle (Degree)	Optimum azimuth angle (Degree)	Yearly PV energy production (kWh)	Yearly in-plane irradiance (kWh/m^2)
Hull	42	-9	4010	1350
Cottingham	42	0	3940	1330
Scarborough	42	-7	3880	1300
Brotton	43	0	3810	1300
Driffield	42	-9	3740	1260
Doncaster	41	-8	3690	1250
Barnsley	41	-6	3640	1220
Pocklington	41	-10	3640	1230
Wakefield	41	-6	3630	1220
Rotherham	40	-7	3600	1210
York	41	-10	3590	1210
Sheffield	40	-6	3590	1210
Selby	41	-10	3580	1210
Redcar	42	-8	3570	1200
Leeds	40	-7	3570	1200
Harrogate	40	-5	3560	1200
Dewsbury	40	-4	3540	1200
Batley	40	-6	3540	1200
Thornaby	41	-8	3530	1192
Ripon	41	-5	3520	1190
Huddersfield	39	-1	3520	1160
Halifax	39	-2	3510	1180
Thirsk	41	-9	3500	1180
Bradford	40	-4	3480	1180
Northallerton	41	-6	3460	1170
Keighley	38	1	3350	1130

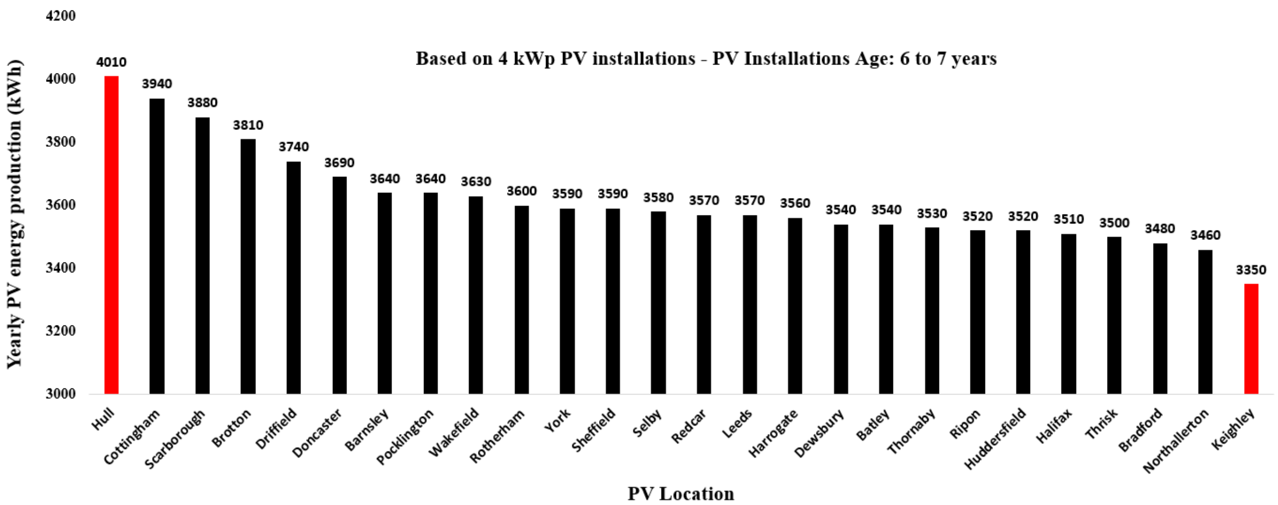


Fig. 5. *Yearly energy production in kWh based on 4 kWh PV systems installed in each studied location*

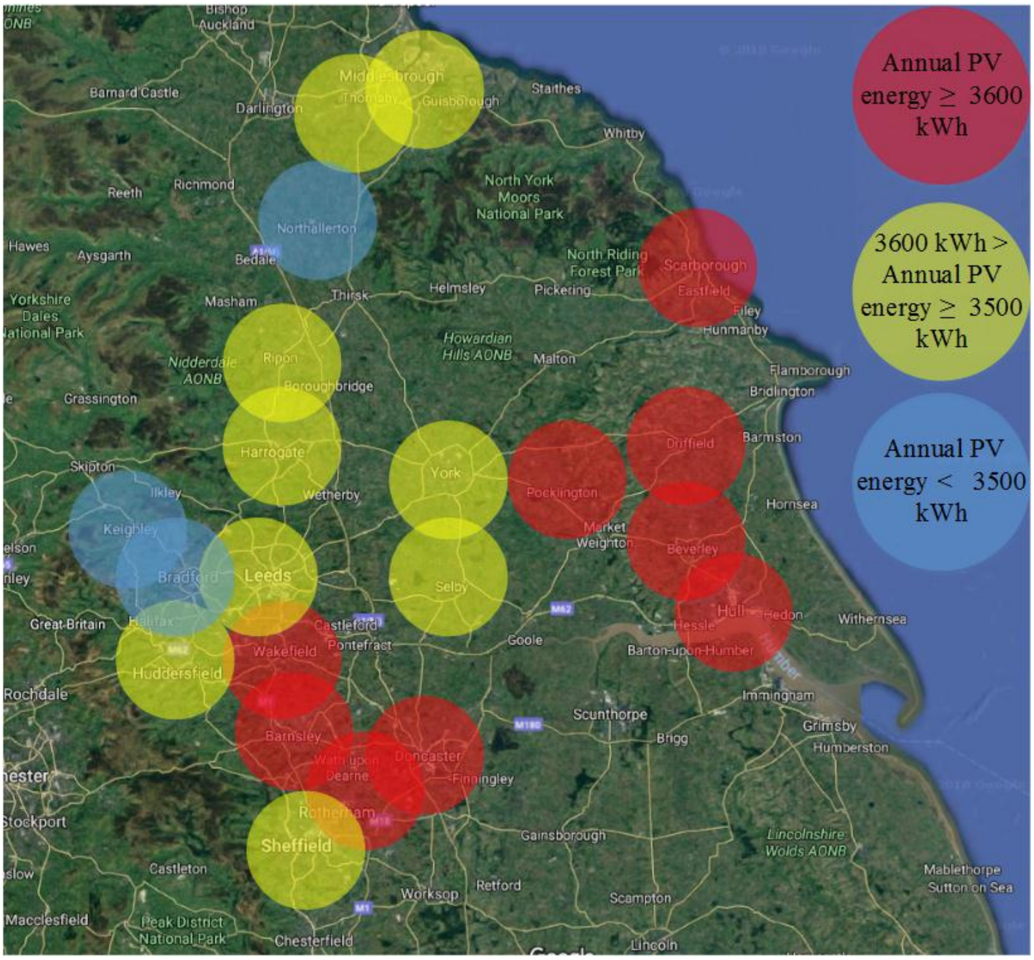


Fig. 6. *Map presenting the annual energy production in twenty-six locations in the Yorkshire region of the UK; the analysis is based on 4 kWp PV installations*

As described earlier, Hull has the highest annual energy production among all other tested locations within the Yorkshire region. The analysis of the tilt angle for this specific city will be described using three different PV systems of capacity 4 kWh installed at 42º, 38º, and 32º tilt angle respectively. The azimuth angle for all tested PV installation is at -8º.

Fig. 7(a) shows the distribution of the examined PV installations. The PV system installed at tilt angle 42º is 538m apart for the PV system installed at tilt 32º, whereas 471 meters is the distance between PV systems installed at tilt angle 32º and 38º.

Historic data for PV energy production over the last six years is shown in Fig. 7(b). It is evident that the PV system installed at tilt angle 42º produces the highest output energy. This result is identical to the observed optimum tilt angle reported previously in Table 2 (Hull: ideal tilt angle 42º, ideal azimuth angle -9º).

The average energy production for the examined PV installations in the last six years (2012 – 2017) are presented as follows:

- Tilt angle 42º: 4053 kWh
- Tilt angle 38º: 3992 kWh
- Tilt angle 32º: 3951 kWh

The difference between the annual energy production for the PV system installed at 42º and 38º is 61 kWh, there is greater drop in the annual energy production compared to the PV system installed at 32º, which is equal to 102 kWh.

For better explanation, the observed data in the last year (2017) is shown in Fig. 7(c). The PV system with tilt angle 42º almost generates the highest energy production in all months, expect in May, June, and July. The annual PV energy production for the three examined PV installations in 2017 is equal to:

- Tilt angle 42º: 4046 kWh
- Tilt angle 38º: 3985 kWh
- Tilt angle 32º: 3940 kWh

The loss in the energy due to change in the tilt angle of the PV installations could potentially reach up to 106 kWh in 2017.

In conclusion, this section describes the impact of the tilt angle on the energy production of PV installations based on a historic data of six years. Three PV installations located in Hull were studied. The PV installations have different tilt angle. It was found that the energy loss could reach up to 106 kWh per year due to the change in the tilt angle of a PV installation. The optimal tilt angle found to be at 42º.

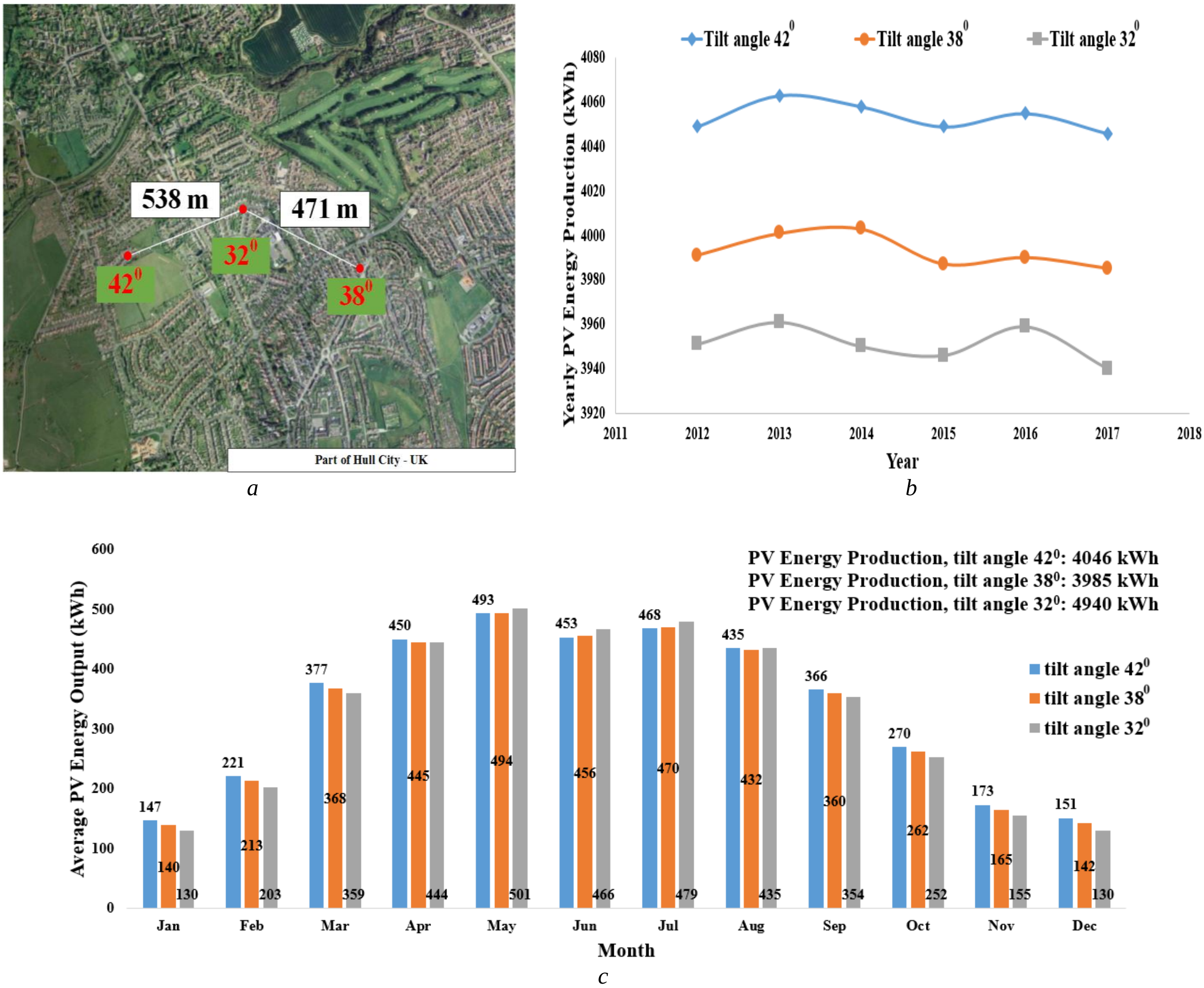


Fig. 7. *Evaluating the impact of tilt angle based on three different PV systems installed in the city of Hull* ***(a)*** *Map showing the examined PV installations in Hull including the tilt angle,* ***(b)*** *Six years annual energy production of the examined PV installations at different tilt angle,* ***(c)*** *Monthly energy production of the examined PV installations in 2017*

5. Probabilistic projections, error analysis, and various metrological conditions

The provision of probabilistic and error analysis projections is the major improvements which many researchers worldwide relies on to extensively prove/disapprove the chance of an action to accrue. Probabilistic projections assign a probability to different possible weather conditions outcomes, recognizing that: (i) we cannot give a single answer, and (ii) giving range of possible outcomes is better, and can help with marking robust adaption for the results decisions. However, at the same time, it will limit the findings within a range of thresholds.

In previous sections, including the findings of the annual energy production of various PV systems installed in various locations across Yorkshire region – UK, it is unlikely to determine the absolute probability of the annual energy projections for the PV installations. For example, in section 3, it was found that the PV system installed in the Hull region at tilt angle of 42^{o} achieves the maximum annual energy; however, there are several reasons that might effect of future annual energy projections.

Hence, this section will describe the use of Cumulative Distribution Function (CDF) [31], which will give a reasonable range of possibilities that the annual energy projection would be within specific thresholds.

According to the observed annual energy shown previously in Fig. 6, it is noticed that coastal PV sites generate the highest annual energy comparing to north and south PV locations. Therefore, this section presents the CDF modelling from this sub-location in Yorkshire region. A geographical distribution of the locations are shown in Fig. 8, and classified as follows: Yorkshire coastal locations, north Yorkshire, and south Yorkshire.

For each sub-location, several PV sites were modelled using a histogram chart as shown in Fig. 9. The number of PV sites are equal to 40, the x-axis corresponds to the annual energy generation, whereas y-axis presents the frequency of the PV sites to produce certain annual energy threshold.

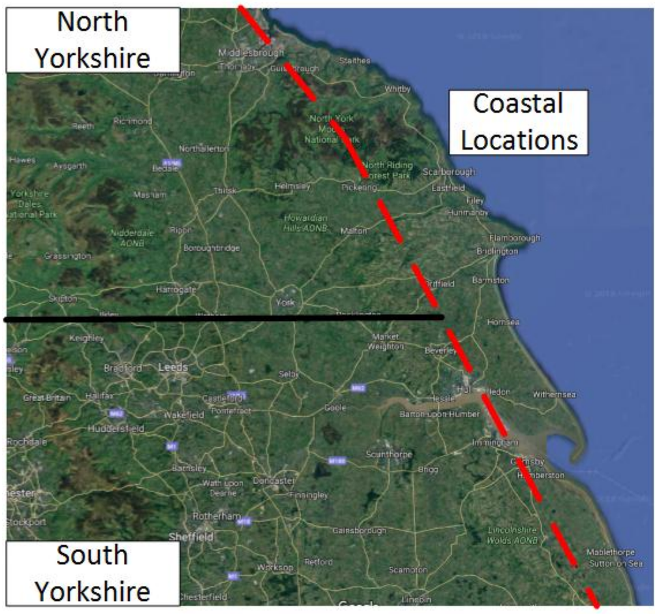


Fig. 8. *Yorkshire land geographical distribution*

The annual energy production for the coastal PV sites are higher than the PV sites in both north and south locations. The mean energy production for all locations are shown in Fig. 9, and summarized as follows:

- Coastal PV sites: 3758 kWh
- South PV sites: 3608 kWh
- North PV sites: 3430 kWh

According to Fig. 10, the CDF models in the coastal region, we would expect 80% of the PV installations sited in this area to generate an annual energy of 3740 kWh. The 80% threshold is a reasonable probability selection, since it has been used as a rule of thumb in order incorporate the data of a CDF model to actual representation of its findings, this practice has been widely utilized [32 - 34]. Similarly, according to the south CDF model shown in Fig. 10, we would expect 80% of the PV installations sited in this area generate an annual energy production of 3630 kWh. This is less than the coastal PV sites by 3740 – 3630 = 110 kWh.

Remarkably, the minimum observed annual energy production is the northern Yorkshire. Where 80% of the installations are expected to generate 3500 kWh, which is less than the coastal PV sites by 240 kWh. This is because this area has the minimum solar radiation compared to the coastal and south locations.

There are two fundamental reasons that the coastal PV sites would expect to generate more energy compared to the north and south location:

- The coastal PV sites have lower ambient temperature compared to the PV systems installed in the north and south Yorkshire
- The annual solar irradiance is always greater than 1240 kWh/m^2, compared to the south and north locations which have an annual solar radiation of 1201 kWh/m^2, and 1158 kWh/m^2 respectively.

In summary, the histogram plot and the CDF models illustrate that the PV location play a dynamic role in the annual energy production, since each of the observed location differs in its annual solar radiation and temperature levels, thus it would affect the total generation for the PV sites. In addition to that, the tilt and azimuth angle varies per location, in which it must be considered when installing the PV system.

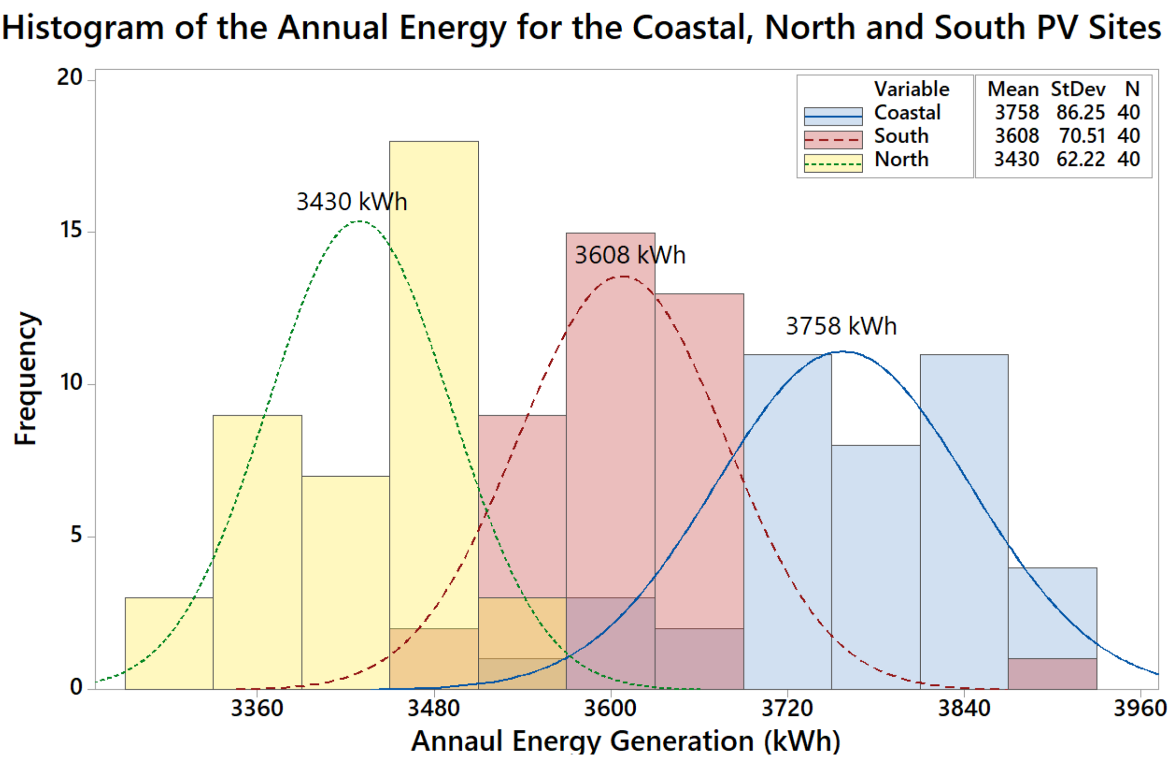


Fig. 9. *Histogram for the annual energy generation for coastal, north and south PV sites in Yorkshire region*

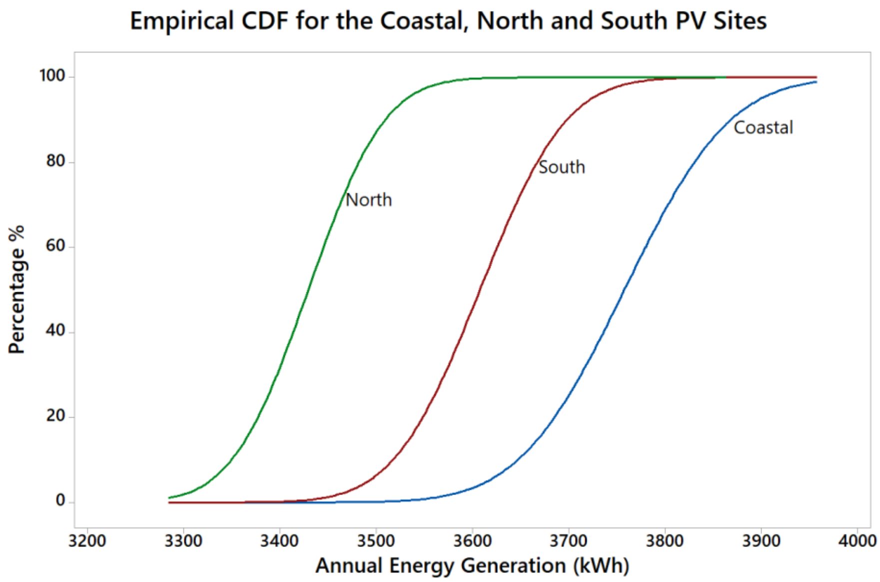


***Fig. 10.** CDF model for the studied locations in Yorkshire including Coastal, North, and South site plots*

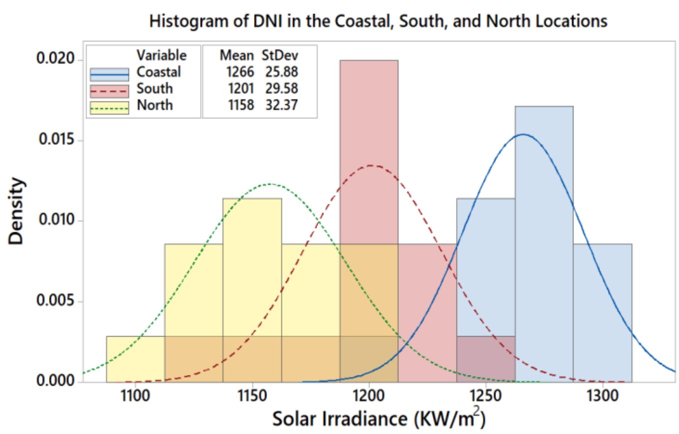
The variations in the output energy generation for the coastal, south, and north locations are due to various factors such as fluctuations in the solar irradiance, ambient temperature, shading factors, and cloudiness.

In Fig. 11, we present the actual average data for the direct normal irradiance (DNI) and the ambient temperature in the coastal, north and south locations, the data are averaged over a period of 25 years [35]. According to Fig. 11(a), it is noticed that the mean direct normal irradiance in the coastal areas are the highest; 1266 kW/m^2. Whereas, the mean irradiance in the south and north is equal to 1210 kW/m^2 and 1158 kW/m^2, respectively. This result confirms that coastal PV systems would potentially generate more output power compared to the south PV system, ranked the second optimum location.

A well-known fact in photovoltaic power generation is that the increase in the ambient temperature results a decrease in the output energy. Fig. 11(b) shows that the mean temperature in the coastal locations is the lowest (8.88 °C), compared to south (9.14 °C) and north (9.38 °C) areas. Resulting a higher output energy production for the PV modules installed in the cost. Accordingly, this is the second metrological reason why coastal locations in Yorkshire are the optimum for PV installations compared to northern and southern regions.

There are many other metrological conditions which affect a PV installation output power. One of the major effects is PV hot-spotting; shown in Fig. 12(a); due to air frost. Air frost occurs when the air temperature falls to or below the freezing point of water. Hot-spotting is a reliability problem in photovoltaic (PV) panels where a mismatched cell heats up significantly and degrades PV panel output-power performance [36]. A high PV cell temperature due to hot spotting can damage the cell encapsulation and lead to second breakdown, where both cause permanent damage to the PV panel.

The average number of air frost days per year in the last 25 years for each area is shown in Fig. 12(b) [35]. It is evident that coastal locations had the lowest number of frost days (31.77) compared to south (45.15) and north (53.38) areas. Once again, these results confirm coastal PV installations are less likely to have defective/hot-spots. Thus, confirming higher generation of the output power, less reliability problems, less mismatching conditions, and PV modules affected by a preferred metrological conditions.



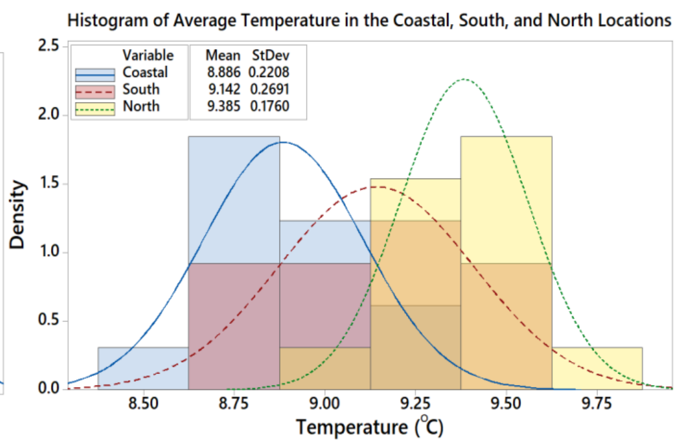


***Fig. 11.** Histogram of the normal distribution of the average solar irradiance and temperature in the studied locations **(a)** Average solar irradiance data, **(b)** Average temperature data*

Finally, the influence of PV partial shading conditions reducing the amount of power generated is considered. Main cause of partial shading is moving clouds. Fig. 12(c) shows the average cloud cover in the examined PV locations. As noticed, coastal locations are affected by low level of clouds per annum, whereas partially/medium cloud cover is affecting northern locations. Finally, southern locations are affected by heavy or heavy percentile clouds compared to northern and coastal locations.

Therefore, this result confirms that PV installations in the cost are less likely to be affected by clouds compared to northern and southern PV installations. As a result, this would increase the annual energy production in the PV systems and decrease the loss in the instantaneous PV power due to moving clouds.

In summary, this section demonstrated an overview of the probabilistic and error analysis as well as four metrological conditions (DNI, ambient temperature, air frost, and cloudiness) affecting PV installations energy production.

6. Conclusion

This paper analyses the optimum tilt and azimuth angle for PV installations in twenty-six locations within the county of Yorkshire, UK. Major contribution are as follows:

- Presenting the optimum tilt and azimuth angle for all studied locations. The analysis is based on actual measured data for hundreds of PV installations over a period of 6 to 7 years. On average, it was found that the tilt and azimuth angle is equal to 40º and -6º, respectively.
- Based on 4 kWp PV installations observed in all studied locations, a map presenting the annual energy production in the twenty-six locations is drawn. The maximum annual energy production found in the coastal site of Hull city, whereas the minimum observed in northern site of Keighley.

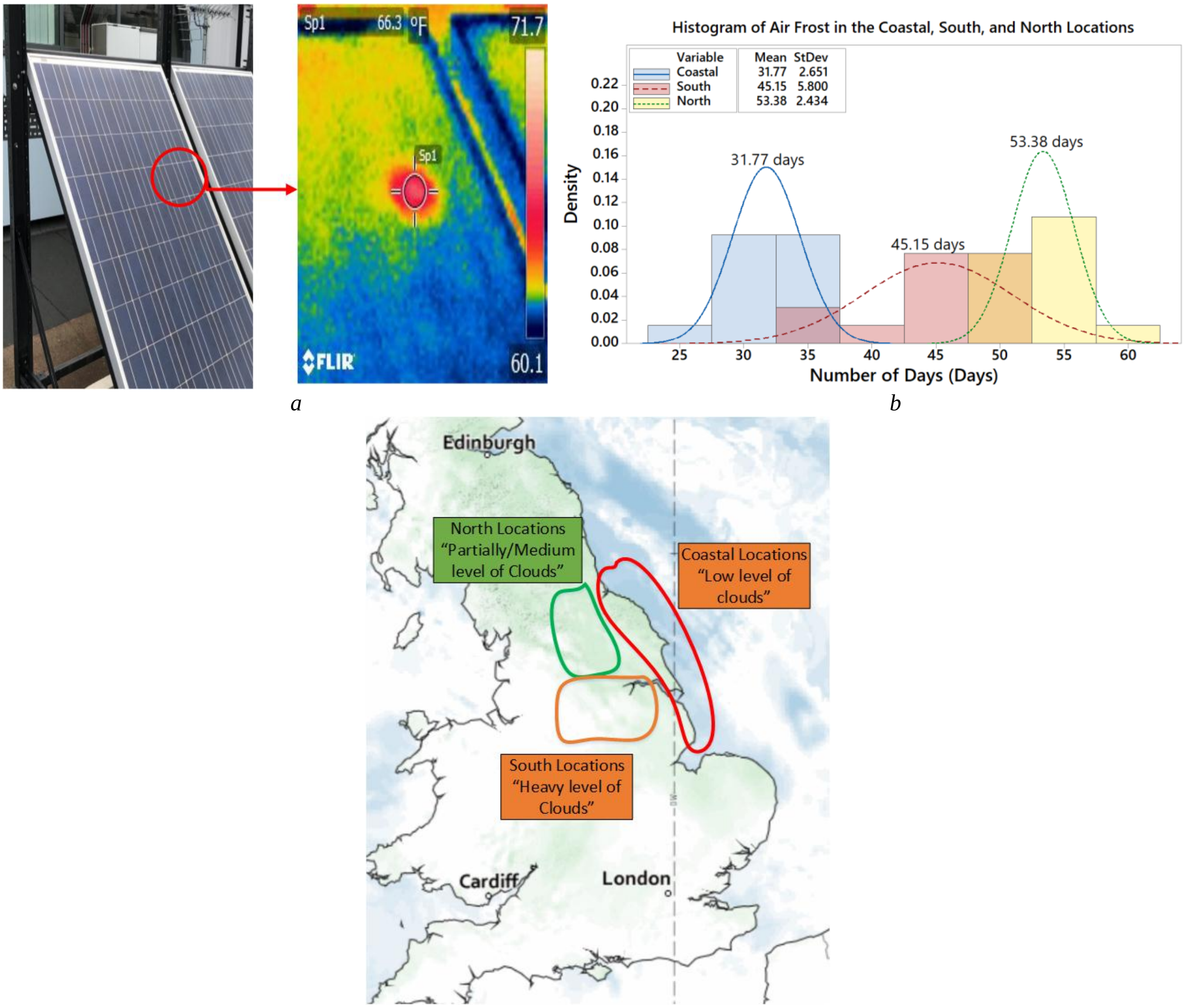


Fig. 12. *Air frost and cloud distribution in the examined locations*
(a) *Hot-spots in the PV module,* ***(b)*** *Histogram of the average days of air frost in coastal, south and north locations,* ***(c)*** *Geographical map of the average cloud the studied locations*

- The main four causes for the loss in the PV energy, including the direct solar irradiance, ambient temperature, air frost, and the cloud distribution.
- Evidently, it was found that coastal locations had the highest DNI, lower level of ambient temperature (acting as cooling factor for PV installations), least number of air frost (compare to southern and northern locations), and has the least cloud cover (certainly, less partial shading conditions, and more solar sunshine hours).

In future, it is intended to explore the use of recent study and the proposed methodology to investigate the regional annual energy production of the entire UK including all districts and counties.

7. References

[1] Yeh, W. C., Huang, C. L., Lin, P., Chen, Z., Jiang, Y., & Sun, B. (2017). Simplex simplified swarm optimisation for the efficient optimisation of parameter identification for solar cell models. IET Renewable Power Generation, 12(1), 45-51.

[2] Sangrody, H., Sarailoo, M., Zhou, N., Tran, N., Motalleb, M., & Foruzan, E. (2017). Weather forecasting error in solar energy forecasting. IET Renewable Power Generation, 11(10), 1274-1280.

[3] Mazumder, M. K., Horenstein, M. N., Joglekar, N. R., Sayyah, A., Stark, J. W., Bernard, A. A., ... & Griffin, A. C. (2017). Mitigation of Dust Impact on Solar Collectors by Water-Free Cleaning With Transparent Electrodynamic Films: Progress and Challenges. IEEE Journal of Photovoltaics, 7(5), 1342-1353.

[4] Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., & Mather, P. (2018). Output-Power Enhancement for Hot Spotted Polycrystalline Photovoltaic Solar Cells. IEEE Transactions on Device and Materials Reliability, 18(1), 37-45.

[5] Dhimish, M., Holmes, V., Mather, P., & Sibley, M. (2018). Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance. Solar Energy Materials and Solar Cells, 179, 72-79.

[6] Hosseini, S., Taheri, S., Farzaneh, M., & Taheri, H. (2018). Modeling of Snow-Covered Photovoltaic Modules. IEEE Transactions on Industrial Electronics.

[7] Dhimish, M., Holmes, V., P. Mather, C. Aissa, & M. Sibley. (2018). Development of 3D graph-based model to examine photovoltaic micro cracks. Journal of Science: Advanced Materials and Devices, 3(3), 380-388.

[8] Dhimish, M., Holmes, V., Dales, M., & Mehrdadi, B. (2017). Effect of micro cracks on photovoltaic output power: case study based on real time long term data measurements. Micro & Nano Letters, 12(10), 803-807.

[9] Buerhop, C., Pickel, T., Patel, T., Fecher, F. W., Zetzmann, C., Camus, C., ... & Brabec, C. J. (2017). Analysis of inhomogeneous local distribution of potential induced degradation at a rooftop photovoltaic installation. IET Renewable Power Generation, 11(10), 1253-1260.

[10] Mani, M., & Pillai, R. (2010). Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renewable and Sustainable Energy Reviews, 14(9), 3124-3131.

[11] Xu, R., Ni, K., Hu, Y., Si, J., Wen, H., & Yu, D. (2017). Analysis of the optimum tilt angle for a soiled PV panel. Energy Conversion and Management, 148, 100-109.

[12] Kaddoura, T. O., Ramli, M. A., & Al-Turki, Y. A. (2016). On the estimation of the optimum tilt angle of PV panel in Saudi Arabia. Renewable and Sustainable Energy Reviews, 65, 626-634.

[13] Sedraoui, K., Ramli, M. A., Mehedi, I. M., Hasbi, M., & Hiendro, A. (2017). Optimum orientation and tilt angle for estimating performance of photovoltaic modules in western region of Saudi Arabia. Journal of Renewable and Sustainable Energy, 9(2), 023702.

[14] Le Roux, W. G. (2016). Optimum tilt and azimuth angles for fixed solar collectors in South Africa using measured data. Renewable Energy, 96, 603-612.

[15] Skeiker, K. (2009). Optimum tilt angle and orientation for solar collectors in Syria. Energy Conversion and Management, 50(9), 2439-2448.

[16] Georgitsioti, T., Pillai, G., Pearsall, N., Putrus, G., Forbes, I., & Anand, R. (2015). Short-term performance variations of different photovoltaic system technologies under the humid subtropical climate of Kanpur in India. IET Renewable Power Generation, 9(5), 438-445.

[17] Maghrebi, M. J., & Nejad, R. M. (2017). Performance evaluation of floating solar chimney power plant in Iran: estimation of technology progression and cost investigation. IET Renewable Power Generation, 11(13), 1659-1666.

[18] Lave, M., & Kleissl, J. (2011). Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental United States. Renewable Energy, 36(3), 1145-1152.

[19] Bakirci, K. (2012). General models for optimum tilt angles of solar panels: Turkey case study. Renewable and Sustainable Energy Reviews, 16(8), 6149-6159.

[20] Jafarkazemi, F., & Saadabadi, S. A. (2013). Optimum tilt angle and orientation of solar surfaces in Abu Dhabi, UAE. Renewable energy, 56, 44-49.

[21] Armstrong, S., & Hurley, W. G. (2010). A new methodology to optimise solar energy extraction under cloudy conditions. Renewable Energy, 35(4), 780-787.

[22] Stanciu, C., & Stanciu, D. (2014). Optimum tilt angle for flat plate collectors all over the World–A declination dependence formula and comparisons of three solar radiation models. Energy Conversion and Management, 81, 133-143.

[23] Rawat, R., Kaushik, S. C., & Lamba, R. (2016). A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. Renewable and Sustainable Energy Reviews, 57, 1506-1519.

[24] Akhtar, F., & Rehmani, M. H. (2015). Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review. Renewable and Sustainable Energy Reviews, 45, 769-784.

[25] Anwari, M., & Bouchekara, H. (2018). Estimation of solar radiation on PV panel surface with optimum tilt angle using Vortex Search algorithm. IET Renewable Power Generation.

[26] Paiva, G. M., Pimentel, S. P., Marra, E. G., & Alvarenga, B. P. (2017). Analysis of inverter sizing ratio for PV systems considering local climate data in central Brazil. IET Renewable Power Generation, 11(11), 1364-1370.

[27] Antonanzas, J., Urraca, R., Martinez-de-Pison, F. J., & Antonanzas, F. (2018). Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: A study across Europe. Solar Energy, 163, 122-130.

[28] Alsadi, S. Y., & Nassar, Y. F. (2017). Estimation of Solar Irradiance on Solar Fields: An Analytical Approach and Experimental Results. IEEE Transactions on Sustainable Energy, 8(4), 1601-1608.

[29] Mason, N. B. (2016). Solar PV yield and electricity generation in the UK. IET Renewable Power Generation, 10(4), 456-459.

[30] Horoufiany, M., & Ghandehari, R. (2017). Optimal fixed reconfiguration scheme for PV arrays power enhancement under mutual shading conditions. IET Renewable Power Generation, 11(11), 1456-1463.

[31] Jacobson, M. Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Solar Energy, 169, 55-66.

[32] M. Dhimish, V. Holmes, P. Mather & M. Sibley. (2018). Preliminary assessment of the solar resource in the United Kingdom, Clean Energy, zky017, doi: 10.1093/ce/zky017.

[33] Lujano-Rojas, J., Dufo-López, R., Bernal-Agustín, J. L., Domínguez-Navarro, J. A., & Catalão, J. P. (2018). Probabilistic methodology for estimating the optimal photovoltaic capacity in distribution systems to avoid power flow reversals. IET Renewable Power Generation.

[34] Nikmehr, N., & Najafi-Ravadanegh, S. (2015). Optimal operation of distributed generations in micro-grids under uncertainties in load and renewable power generation using heuristic algorithm. IET Renewable Power Generation, 9(8), 982-990.

[35] Met Office. (2018). UK and regional series. Link: https://www.metoffice.gov.uk/climate/uk/summaries/datasets.

[36] Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., & Mather, P. (2018). PV output power enhancement using two mitigation techniques for hot spots and partially shaded solar cells. Electric Power Systems Research, 158, 15-25.